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THE FEASIBILITY OF FORMING A BORON FIBER-REINFORCED ALUMINUM COMPOSITE BY A HOT EXTRUSION PROCESS

WENDELL J. MEYERER

Captain, USAF

TECHNICAL REPORT AFML-TR-68-127

AUGUST 1968

AIR FORCE MATERIALS LABORATORY
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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FOREWORD

This report was initiated in the Air Force Materials Laboratory under Project No. 7351, "Metallic Materials," Task No. 735107, "Metal Matrix Composites." It was released by the author 1 January 1968 for publication as a technical report.

This report was authored by Captain Wendell J. Meyerer of the Advanced Metallurgical Studies Branch, Metals and Ceramics Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio. It covers a study conducted from December 1965 to January 1968.

The author wishes to express his appreciation to Mrs. Kathryn Branch and Mr. Eugene Wooley for the photomicrographs, Mr. Larry Bates for the electron microscopy, and to Mr. V. DePierre of the Processing and Nondestructive Testing Branch, Air Force Materials Laboratory, for advice and use of their facilities.

The author also wishes to express his gratitude to Dr. J. A. Herzog for his guidance on this project.

This technical report has been reviewed and is approved.

C. T. LYNCH
Chief, Advanced Metaullurgical
Studies Branch
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ABSTRACT

This study was performed to ascertain the feasibility of forming a boron fiber-reinforced aluminum composite by a hot extrusion process. Post-extrusion examination revealed that fiber breakup was excessive, but the length to diameter ratio for most of the filaments was great enough to effect a stress-transfer. Thus, both modulus and strength values increased as the volume percent fiber in the specimens increased.

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SECTION I

INTRODUCTION AND BACKGROUND

The current interest in composite materials stems from the philosophy that any future significant contributions will probably employ a combination of two or more very different materials. The goal of such composites would be to utilize the most desirable inherent properties of each constituent to achieve, in effect, a new class of structural materials. However, the advantages to be gained by combining two different materials must be tempered by the fact that certain other properties are compromised (Reference 1).

Ceramics, while offering good oxidation resistance at elevated temperatures, have the disadvantage of being extremely brittle. However, by compromising certain properties of both a ceramic-type fiber and a metal matrix, one can achieve a new material with a unique set of properties. This new class of materials, while offering great potential, also poses many problems. Generally, to fully utilize the properties of a composite, it must be custom-made for the specific application for which it is intended to be used. That is, a composite's highly anisotropic properties can be "custom-controlled" by such parameters as: type of fibers used, the direction of the fibers, and the volume percent fibers within the metal matrix.

Many problems such as the degree of interaction between the fibers and the metal matrix are extremely important (Reference 2). For instance, mechanical bonding (no chemical interaction between fiber and matrix) may actually be adequate for certain applications. It is believed that chemical bonding between fibers and matrix is more desirable for the efficient transfer of stresses through the matrix. However, too great a reaction between the fiber and matrix could be detrimental since the properties of the fiber might be destroyed. Thus, this problem presents itself as a dilemma. In one case (i.e., sapphire whiskers) certain coatings must be applied to the fiber to achieve any degree of bonding, while on the other hand, certain materials which act as diffusion barriers must be applied to other types of fibers or filaments to prevent overreaction (Reference 4). Nevertheless, with the emergence of new fibrous

materials such as boron filament, silicon carbide filament, and alumina whiskers (Reference 5), laboratory results utilizing such fibers in composites have been encouraging enough (from a metallurgical behavior and a mechanical property standpoint) to warrant further study.

Interest in composites was stimulated by the glass-reinforced plastics technology. The theory for fiber reinforcement of metals has not been well defined since the detailed micromechanics have not been satisfactorily investigated. However, most investigators borrow existing theories from the classical mechanics areas solely concerned with the elastic stress range which leads to the result that for a given strain of the components, the high modulus fibers will bear more of the stress than the lower modulus matrix. This theory must be slightly modified since the plastic matrix behaves in a brittle fashion while a metal matrix will display a degree of ductility. Thus, for a reasonable percentage of the fiber strength to be realized, the metal matrix may be stressed beyond its elastic limits.

The work of Cratchley and Baker (Reference 6) with a continuous silica fiber-reinforced aluminum alloy has demonstrated (by hot pressing aluminum coated silica fibers) room temperature strengths of 140,000 PSI.

Sutton and Chorne (Reference 4) have shown that the short or staple alumina whiskers (by molten infiltration of alumina whiskers with silver) offer reinforcement for silver both at room and at elevated temperatures.

Weeton, Quatinetz, and Herbell (Reference 7) have performed extrusion studies on tungsten with added compounds in order to study the feasibility of producing fiber-bearing composites by the elongation of materials in situ during the extrusion. Their results were encouraging since composites with highly elongated additives ranged from four to 18 times better in stress rupture life at 3000°F than unreinforced specimens of tungsten matrix.

Weeton, Jech, and McDaniels' (Reference 8) fabricated tungsten fiber-reinforced copper composites by molten infiltration showed reinforcement at various volume percent tungsten.

Parikh (Reference 9) with a steel fiber-reinforced silver composite (by hot extrusion) demonstrated that a 20-volume percent addition of 0.5 mil steel filament resulted in a five-fold increase in strength over that of pure silver.

To date, the Advanced Metallurgical Studies Branch of the Air Force Materials Laboratory has investigated boron fiber-reinforced aluminum composites fabricated by various methods among which was a powder metallurgy process. The boron filament was chosen due to its present availability and because it represents the new generation of filamentary materials. The aluminum was selected as a matrix material because of its ease of handling and adaptability to a powder metallurgy process. For convenience, these powder metallurgy specimens were approximately 3/16 inch wide, 3-1/2-inch long, and of variable thicknesses. These powder metallurgical bar specimens have been used to generate data as to the reinforcing effects of these new filaments. Using various fiber configurations, (that is, a). continuous and b). discontinuous filaments within the gage section of the specimen) these powder metallurgical bar composites have demonstrated that the boron filament does have a reinforcing effect on the aluminum matrix (Figure 1).

The method of lay-up and fabrication is extremely tedious since this is entirely a hand process. That is, the boron filaments must be individually placed into the die with the desired amount of powdered aluminum for each bar specimen. It was because of this need for a more production-orientated process that the idea for the subject of this present study was generated. Although hot extrusion was successfully used by Parikh (Reference 10) for fabricating a metal fiber-reinforced metal matrix composite, much skepticism arose when a similar method was suggested for a boron fiber-reinforceed metal system, due to the brittle nature of the boron filament.

SECTION II

STATEMENT OF PROBLEMS

The objectives of this study were many: (1) feasibility of using extrusion as a forming process for a composite of a brittle nonmetallic fiber and ductile matrix; (2) mechanical data for the resultant composites; (3) metallographic cross sections of the extrusion to determine fiber spacing; (4) longitudinal sections to determine fiber alignment; (5) investigation of fiber damage by leaching the fiber from the matrix; and (6) investigation of fiber distribution as a function of extrusion length.

Because of its deficiencies, the early boron fiber was a poor fiber to select for such a study. However, it was indicative of a new class of filamentary materials. The question of optimum particle size distribution arises when using powder metallurgical techniques for fabricating specimens.

SECTION III
PROCEDURE

Prior studies to control the particle size of the aluminum powder yielded a slight increase in modulus values for blank bar specimens, but no apparent increase in tensile strength was observed. Results of a sieve test are given in Figure 2. It was decided to utilize the aluminum powder as supplied by the manufacturer. The powder was preweighed on an analytical balance to insure size uniformity for all the bar specimens (Figure 4-1). The boron filament was supplied through an Air Force contract with Texaco Experiment Station, Alexandria, Virginia. Next the boron filaments were cut to a uniform size on a device which cuts and counts the fibers (Figure 4-2). Then the fibers were cleaned in an acetone solution. The hand lay-up procedure was simple but tedious. For the second extrusion (discontinuous filaments) as well as the third extrusion (continuous filaments), a layer of aluminum powder was placed in the die (Figure 4-3) and leveled by the use of a flat "gage". For the discontinuous filament configuration approximately 35 1-inch boron fibers were placed individually on the powder by the use of a fine tweezer. For the continuous filament configuration approximately 35 3-inch boron fibers were utilized per layer. Care was taken to insure maximum alignment and even distribution of all the fibers. Nevertheless, there was an appreciable degree of misalignment (Figure 3). This lay-up procedure was repeated until six layers of fiber and aluminum powder were obtained for each bar specimen.

More recently a simple jig (Figure 5) was designed which would permit accurate spacing of the layers of filament and powder. (A micrometer controls the male portion of the die.)

The sample was then pressed to a load of 30 tons (75,000 PSI) (Figure 4-4) on a hydraulic press. This entire process was repeated 25 times in order to fabricate 25 bar specimens for each extrusion study. Cans (5.45 inches long and 2.798 inches in diameter) of 2024 aluminum were machined to receive the 25 bar specimens (Figure 4-5).

The can technique was chosen for a variety of reasons: (1) there is less chance of contamination of the composite with other materials (Reference 11). (2) it is a method to utilize the existing bar-specimen technology; and (3) economics (boron filament was expensive at the time this study was performed.)

Since the bar specimens have a rectangular shaped cross section, shims were needed to completely fill the 1-inch diameter cavity within the 2024 can (Figure 4-6). Once the shims were fitted and tightly packed with the bar specimens in the cavity, the rear end of the can was sealed with aluminum pins. The billet was then prepared for extrusion (Figure 4-7).

The billet was preheated to 800°F within the extrusion press for one hour and then was extruded at the very slow rate of approximately 1.6 inch per minute with a reduction ratio of 10:1. The resultant bar was photographed for recording surface conditions. The the extruded bar (approximately 48-inch long) was cut into 1-inch and 3-inch sections for metallography and tensile specimens respectively (Figure 4-9, 10). Care was taken to inscribe the position, number, and the extrusion direction on all pieces cut from the extruded bar.

The metallographic specimens were polished for fiber condition and spacing. Although many methods have been tried both within the Air Force Materials Laboratory and other research establishments, no satisfactory technique has been established to successfully polish both the boron filaments and the metal matrix with complete absence of relief (Reference 12). This is due to the difference in hardness between boron fiber and pure aluminum (V.H.N. of 1372 versus 45 respectively).

Macrophotographs were taken to leached fibers from each metallographic section.

The 3-inch sections of the extruded bar were machined into tensile specimens. Extreme difficulty was encountered when the cutting tool of the lathe encountered a boron fiber. SR-4 strain gages were cemented to the tensile specimens. Since doubt arose as to the validity of 1/4-inch gages, Huggenberger mechanical strain gages with a 1-inch gage length were attached to the specimens at 90° to the SR-4 gages. A Vickers hardness test was made across the face of one of the longitudinal specimens.

SECTION IV

DISCUSSION AND RESULTS

Post-extrusion examination of the surface condition of the composite bar revealed cracking. (Both the occurrence and the depth of these cracks increase from the front to the rear of the extruded bar.) Several factors could be regarded as possibly contributing to such a surface condition, as suggested by Pearson and Parkins (Reference 12): (a) differential stresses set up because of unequal distribution of flow through the die aperture, die roughness, and lubricant; (b) a rise in the temperature of the metal due to heat generated by internal and external friction in the course of deformation. Although all of the above factors could have contributed to the surface condition, it is believed that excessive heat during the extrusion was the major factor.

Upon examination of the cross section of the metallographic specimens of the second extrusion (1-inch sections), Specimens 7 through 9 exhibited void space between the composite core and the 2024 case. It is believed that this condition was a result of residual void space when the bar specimens and shims were fitted into the cavity of the 2024 can prior to extrusion. It is also believed that this problem can be overcome by a more careful fitting of the core and by using specimens to make a square cross sectional area and then machining the whole composite "bundle" to a round configuration. This would make the use of shims unnecessary. It is hopeful that a technique now under consideration will eliminate the problem of shims (i.e., isostatic pressing).

Although the density of the cold pressed bar specimens was good, (average of 97 percent theoretical density) it is believed that the hot extrusion densified the core area to nearly theoretical limits. Commonly aluminum powders have as much as a 20 Å layer of oxide around each particle (analysis showed that the oxygen content of the as-received powder and the final composite remained the same - 0.5 percent). Normally this would be disadvantageous; however, cold pressing conditions utilizing the high pressures on such a small specimen could have created enough force to break up this oxide layer into a fine dispersement. Likewise, these high pressures for such a dimensionally small

bar specimen could have induced near-isostatic pressing conditions. Efforts are presently underway to establish the validity of this assumption utilizing electron microscopy. (However, green strengths of these cold-pressed specimens are more than adequate.)

Generally, the inter-fiber spacing and fiber alignment throughout every polished section is typified by the macrophotos (Figure 6). However, those specimens with poor filament spacing were fractured by gross matrix flow. The degree of fiber distribution over the length of the extrusion bar was computed on the basis of fiber occurrence in these cross sections.

The purpose of the longitudinal sections was to indicate the alignment of the fibers as a result of the extrusion process. Generally the alignment was fair for both extrusions although areas of greater fiber concentration (Specimens 9 and 11) displayed a greater deviation from the extrusion direction. During polishing of the longitudinal specimens it was observed that some fibers had a tendency to pull out and scratch the specimen surface. Closer observation revealed that when the depth of polishing exceeded the reacted tungsten substrate of the boron fiber, the fiber would be prone to pull out.

The general unevenness of the core area as seen in the longitudinal sections could have been induced by unevenness of core density because of the shims or a restraining effect. This restraining effect could have been caused by the presence of localized fiber concentrations. Without becoming too involved in the extrusion mechanics, more uniform deformation of the billet can be achieved with small angle dies. Likewise Dieter suggests that additional control over deformation may be obtained by changing the length of the bearing section in the die (Reference 13). To suggest some of the interdependence of the extrusion variables, refer to Figure 7. The potential of the extrusion method for fabricating composites remains a subject to be investigated.

Leached filaments from the 1-inch metallographic sections were examined microscopically. Filaments having the greatest length to diameters (approximately 100:1) were located near the area of maximum filament concentration (center of filament distribution curve). Those filaments which suffered the greatest

damage were located at the extremities of the extruded bars (Figure 8). Subsequent work has demonstrated that it is possible to avoid a "normal" distribution and produce a relatively constant distribution over the length of the extrusion. Likewise, increased initial billet length should induce a relatively constant filament distribution.

The 3-inch sections to be used for mechanical testing were machined shown in Figure 4. The actual mechanical testing was performed on an Instron machine with the 0 to 10,000 pound load cell. Originally it was planned to utilize the full 1-inch gage length of the tensile specimens for the strain measurement. However, 1-inch SR-4 gages were unavailable at the time the specimens were tested. In lieu of the 1-inch strain gage, 1/4-inch gages were used; the use of these gages raised an element of doubt as to the validity of the results since the composite, by its very nature, is not a homogeneous material and could be influenced by localized variation in strain. That is, concentrations of the high modulus boron filaments at or near the surface of the test specimen could have influenced the strain in the localized regions near the filaments, thus, false strain readings could occur if the strain measuring device was small and was in the proximity of the filament. As a result of these reflections, it was believed that the larger the strain gage the better statistical average of these localized strain restraints and better strain measurement to reflect the behavior of the whole composite.

Two Huggenberger mechanical extensionmeters were used in conjunction with the two SR-4 gages and the results were compared. The comparison of the results of the two types of gages, when plotted on the same graph, were so close that all previous doubts were queiled.

The crosshead speed for all tests was 0.005 inch per minute. Most of the tests were performed in 50-pound load increments. That is, every time a 50-pound load was attained and readings were taken, the load was dropped back to zero to ascertain the amount of permanent strain to insure elastic measurements (Figure 9). Near the yield point the mechanical gages were taken off.

All fractures occurred in the gage section. However, one disturbing fact was apparent. In the second extrusion, for certain tensile specimens, some of the 2024 can or shim material was included in the machined gage section. Thus the apparent tensile strength values for a group of the specimens were misleading since the strong alloy boosted the ultimate tensile strength of the tensile specimen. It was interesting to note that during the actual testing, as the section of the specimen composed of the alloy failed, the indicated load on the automatic recorder simultaneously dropped. These strips of 2024 alloy at the specimen surface were observed to fracture before the composite portion of the specimen, and the failure of the 2024 material was accompanied by a load drop on the load-elongation curve, followed by further elongation of the composite portion (Figure 10). "Apparent" tensile strength values refer to loads recorded immediately after fracture of 2024 material and the cross-sectional area of only the composite portion of the specimen. Thus, one can extrapolate to determine the actual strength of the composite based on the known area of the composite in the fracture section. That is, the contribution to the ultimate tensile strength due to the presence of 2024 must be accounted for in order to make a reasonable comparison among the various tensile specimens. Consequently, when load values were taken from the automatic recorder graph paper at the point where the 2024 shim material was observed to fail rather than at the point corresponding to the apparent ultimate tensile strength of the specimen, the tensile values were reasonable.

For this study the modulus increased as the fiber content of each specimen increased. For instance, tensile Specimen 10 (second extrusion) possessed the highest volume percent fiber (5.95), and it also displayed the highest modulus (13.5×10^6 PSI). On the other hand, the specimen with a low volume percent fiber (1.6) (second extrusion) displayed the lower modulus of 10.65×10^6 PSI. Figure 16 summarizes the results of the study and shows a comparison of raw experimental results versus compensated results. Generally, the compensated experimental values followed those predicted theoretically. Interestingly enough Specimen 10 (the only specimen which showed no traces of 2024 shim material in the gage section) also showed remarkable agreement with theoretical modulus values using the common Law of Mixtures.

$$E_c = E_f V_f + E_m V_m$$

$$E_c = (55 \times 10^6 \text{ PSI})(.06) + (10.5 \times 10^6 \text{ PSI})(.94)$$

$$E_c = 3.3 \times 10^6 \text{ PSI} + 9.9 \times 10^6 \text{ PSI}$$

$$E_c = 13.2 \times 10^6 \text{ PSI}$$

where

E_c = modulus of elasticity of composite

E_f = modulus of elasticity of fiber

E_m = modulus of elasticity of matrix

V_f = volume percent fiber

V_m = volume percent matrix

(Figure 17)

The third extrusion also displayed a trend toward improved mechanical properties with increasing volume percent boron filament. However, this volume percent filament as represented in a given cross section area was deceiving. The macrophotos of cross sectional areas near the fracture surfaces serve to illustrate this point. Although Specimen 10 (third extrusion) had a high volume percent filament for the given cross sectional area, the distribution of these filaments was not uniform (Figure 18). There was a large area in the center of the specimen which was void of filaments. The macrophoto of the fracture surface of Specimen 10 (third extrusion) shows that this center (matrix) section of the specimen which was void of filament went into gross yielding as it could not support the stresses that the adjacent areas which had filaments could support. Figure 13-b and 15 shows this area of matrix yielding on a macro scale. Replicas of this same area (Figure 13) show evidence of ductility and slip on a micro scale. Thus, if fiber spacing and orientation is not adequately controlled, the reporting of a certain volume percent fiber in a composite can be misleading.

Another interesting phenomenon occurred during tensile testing. As the composite entered the plastic region, the individual fiber fractures were audible. Sometimes when there were multiple fiber fractures, the automatic recorder

would show a sudden interruption of the yield continuously on the curve. For future work it would be interesting to attach a microphone to the specimen in conjunction with another visual recording device in order to correlate the fiber fractures with the conventional stress-strain curve for a composite specimen.

During testing one particularly interesting phenomenon was observed, that of the propagation of a crack on a specimen surface (Figure 11). The crack was observed to originate in the matrix between two fibers exposed on the surface. Upon further straining of the specimen the crack propagated in both directions. One end of the crack intersected a fiber and was arrested. Upon further straining of the composite specimen the fiber fractured. Soon a hairline crack appeared on the opposite side of the fiber. The specimen then fractured in another location. The inference here is that although there was a visible crack on the specimen the presence of filaments (with sufficient aspect ratios) either on or near the surface (provided there is sufficient bonding) appears to: (1) transfer loads; (2) arrest cracks by absorbing energy associated with crack propagation; and (3) provide a devious path for the crack to follow. Based on observations, the following fracture mechanism is proposed (applicable to this type of composite)

1) A crack nucleates in the matrix or areas where fibers have insufficient aspects ratios to transfer stresses --hence these areas act as voids or notches Figure 12-a
2) As the crack approaches the fiber, two mechanisms may occur:
   a) Failure of the interface (poor bonding).
   b) Transfer of energy through the interface to the fiber - the fiber is loaded to its maximum stress and fails.
   c) The void formed by fiber failure can cause propagation of additional cracks if adjacent fibers cannot transfer the localized stress.

Macrophotos were taken of the fracture surfaces for all specimens tested (Figures 13 and 14). The individual fibers under higher magnification displayed a phenomenon heretofore not observed with common bar specimens. Although some fibers pulled out of the matrix aluminum, bonding was apparently extremely

good since the fiber surface was completely covered with aluminum and the tip of the fiber, rather than being void of matrix material, actually showed a cone of aluminum. Likewise, those filaments which fractured first and pulled out, also showed a high degree of adherence between filament and matrix (Figure 14). Being an inhomogeneous material, (i.e., two-component) it is difficult to accurately describe the fracture surfaces without descriptions of the components. As mentioned previously some fiber pull-out was experienced, but fiber fracture was more prevalent. This indicated not only excellent bonding of the fibers to the matrix material, but also a fiber aspect ratio which was sufficient to transfer stresses.

The actual critical aspect ratio (i.e., that minimum length for a given diameter fiber necessary to affect a stress transfer) (ℓ/d) for the boron fiber in an aluminum matrix has not yet been established. However, the critical aspect ratio for whiskers seems to be between 10 to 100 (Reference 4). Generally, it is believed that a ratio of 20:1 will perform satisfactorily. Cratchley (Reference 14) has reported that Kelly and Tyson obtained ℓ/d values of 2 to 4 for a W/Cu composite system. Likewise, Cratchley himself experimentally found that a length to diameter ratio of 10:1 was sufficient enough to reinforce an aluminum matrix.

Generally, fractures were semi-ductile in nature. That is, there is evidence of ductility, but the fracture zone does not result in excessive necking down. Rather there are localized ductile fractures as evidenced by the aluminum on the tips of the boron filaments.

A greater degree of ductility was exhibited by those specimens which had lower volume percent fibers. Likewise, as the fiber content increased, so did the modulus of the composite. One would expect this behavior since the boron fibers act as a restraint on the matrix thereby hindering normal yielding of the aluminum (Figures 12-a, b and 15). Both Sutton (Reference 4) and Weeton, Jech and McDanels (Reference 8) as well as Parikh (Reference 10) experienced this restraint effect. Sutton asserts that in the region adjacent to the fiber (assuming a good fiber to matrix bond) the elongation of the matrix will be constrained and equal to that of the fiber (Reference 4). Weeton claims four

distinct stages of failure in a composite: (1) elastic deformation of fiber, elastic deformation of matrix; (2) elastic deformation of fiber, plastic deformation of matrix; (3) plastic deformation of fiber, plastic deformation of matrix; and (4) final failure. Since Weeton, et al were working with a W/Cu system, stage (3) is true for their system but probably not for B-Al since the boron fiber has not been observed to exhibit plastic deformation at room temperature.

Although some thought had been given to the processing conditions for this study (i.e., extrusion temperature, speed, reduction, lubricants), it had been firmly believed that these parameters could be optimized. The particular temperature for the extrusion (800°F) was selected since it approached the sintering conditions used for the powder metallurgy bar specimens and this elevated temperature would aid in the flow characteristics for the extrusion. Perhaps a lower temperature would yield better results. Likewise, the reduction ratio could be varied.

Plans are presently underway to study these parameters in greater detail in order to evaluate more adequately the extrusion process as a method of fabricating brittle fiber-reinforced ductile metal matrix composites.

Since the feasibility was established for the early "boron fiber" with all of its aforementioned inherent disadvantages, it is believed that the more flexible, higher strength, higher modulus whiskers (single crystal staple filaments) such as alumina or silicon carbide should meet with much greater success. Subsequent extrusion studies utilizing less than ten percent sapphire (Al_2O_3) whiskers in an aluminum matrix have yielded 130-170 percent improvement in strength values with 160-170 percent improvement in modulus values (over pure aluminum). The hot extrusion method would also provide a means of fabricating a whisker-reinforced metal matrix composite by a process which would be amenable to large size scale-up. When considering the extrusion process as a manufacturing method, the possibilities of usable shapes is unlimited. Certainly, should the extrusion method or variations thereof for fabricating composites be perfected, the possibilities for usable structural shapes (Box, "I" and "T" Beams, Tubes, etc.) would be fascinating. A point often overlooked with this class of materials is the fact that for the first

time in the history of metallurgy - man has a method of controlling and significantly improving the modulus of the base metal with no weight sacrifice and certainly no strength sacrifice. This is probably where these types of composites should be considered for use: (1) in structural members or beams where rigidity is a problem and (2) for use in vibration and damping applications in structures. (As damping is controlled by the modulus of the material.) Certainly, when aluminum can be produced in useful structural shapes with a modulus of 15 to 20 x 10^6 PSI; the rest should be up to the designer.

SECTION V

CONCLUSIONS

1. The feasibility of using an extrusion process for the fabrication of a brittle fiber-ductile metal matrix composite was established.

2. The extrusion process will maintain (and in certain cases enhance) filament orientation.

3. Mechanical properties were enhanced. Strength values increased from 120 to 150% of pure aluminum figures. Modulus values increased from 110 to 170% of pure aluminum figures.

4. Good correlation with the modulus law of mixtures was achieved.

5. During tensile testing, cracks tended to nucleate in the matrix or areas where fibers had insufficient aspect ratios to transfer stresses. (Hence, these areas acted as voids or notches.)

6. From the limited testing, it could be concluded that the presence of filaments (with sufficient aspect ratios) either on or near the surface (provided there is sufficient bonding appears to:
   a) transfer stresses
   b) retard cracks by redistributing the energy associated with crack propagation
   c) provide a devious path for the crack to follow.

REFERENCES

1. A.A. Baker and D. Cratchley, Metallographic Observations on the Behavior of Silica-Reinforced Aluminum Under Fatigue Loading, Applied Materials Research, October 1964, p. 215.

2. L.D. Blackburn, H.M. Burte, F.R. Bonanno, Filament-Matrix Interactions in Metal Matrix Composites, Presented at 12th Sagamore Army Materials Research Conference, 1966, p. 25.

3. R.H. Baskey, Final Report on Fiber Reinforcement of Metallic and Nonmetallic Composites, Clevite Corporation, Mechanical Research Division, ASD-TDR-63-619, July 1963.

4. J. Chorne′ and W.H. Sutton, Potential of Oxide-Fiber Reinforced Metals, Technical Information Series, ASM Seminar on Fiber Composite Materials, Philadelphia, Pennsylvania, October 1964.

5. H.M. Burte, F.R. Bonanno, and J.A. Herzog, "Metal Matrix Composite Materials," Orientation Effects in the Mechanical Behavior of Anisotropic Structural Materials, ASTM STP 405, Am. Soc. Testing Mats. 1966, p. 59.

6. A.A. Baker and D. Cratchley, The Tensile Strength of a Silica Fibre Reinforced Aluminum Alloy, Metallurgia, 69, April 1964, p. 153.

7. T.P. Herbell, M. Quatinetz and J.W. Weeton, Studies of Tungsten Composites Containing Fibered or Reacted Additives, NASA Technical Note, NASA TN D-2757, April 1965.

8. O.L. McDanels, R.W. Jech and J.W. Weeton, Stress Strain Behavior of Tungsten-Fiber-Reinforced Copper Composites, NASA TN-1881, October 1963.

9. N.M. Parikh, Special Structures by Powder Metallurgy, Journal of Metals, 15, 5, May 1963, p. 358.

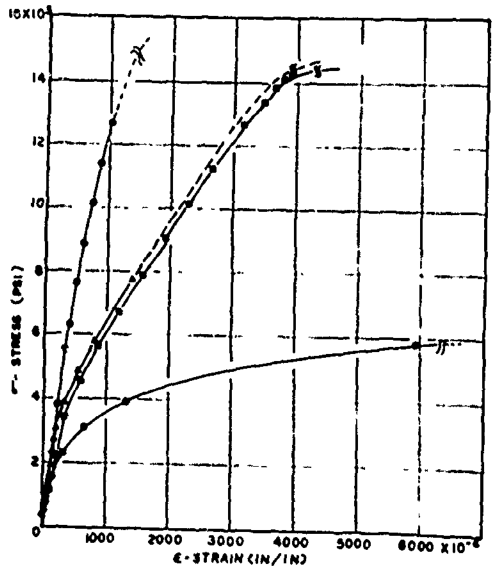
10. N.M. Parikh, Fiber Reinforced Metals and Alloys, ITT Research Institute, Final Report, Contract NOas 60-6081-C, February 1961, p. 1.

11. W.E. Leszynski, Powder Metallurgy, Proceedings of an International Conference held in New York, June 13-17, 1960, Interscience Publishers, Inc., New York, 1961 p. 567.

12. R.N. Parkins and C.E. Pearson, The Extrusion of Metals, John Wiley and Sons, Inc., New York, 1960, p. 257.

13. G.E. Dieter, Jr., Mechanical Metallurgy, McGraw-Hill Book Co., New York 1961, p. 521.

14. D. Cratchley, Experimental Aspects of Fibre-Reinforced Metals, Metallurgical Reviews, 10, 37, 1965.



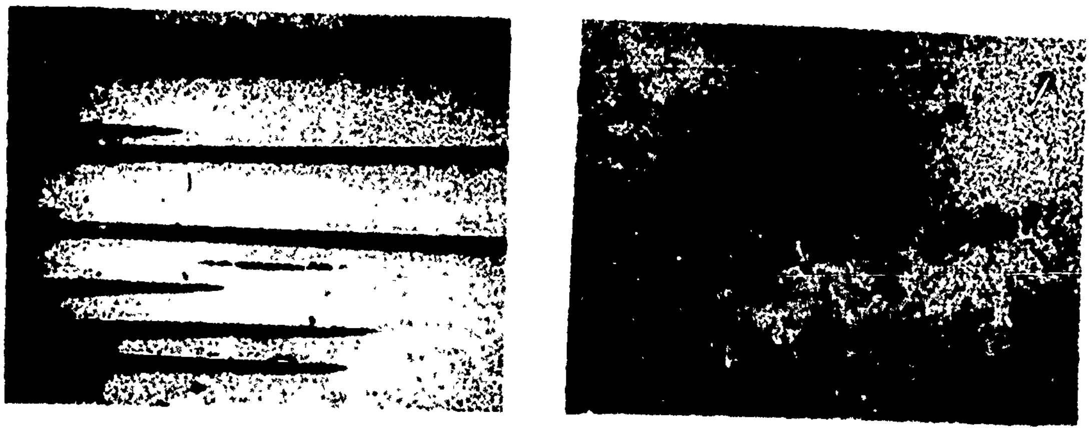
TYPE SAMPLE	ULTIMATE STRENGTH	ELASTICITY MODULUS	VOLUME % FIBER
O Blank	12,900 PSI	10 x 10^6 PSI	0
▲ 100 - 3"	14,287 PSI	12.8 x 10^6 PSI	4.6
◻ 200 - 1"	15,200 PSI	12.7 x 10^6 PSI	7.8
● Extrusion	16,800 PSI	14.2 x 10^6 PSI	9.6

Figure 1. Comparison of Stress Strain Curves for Powder Metallurgical Composites Utilizing Various Fiber Configurations.

SIEVE SIZE	PER CENT
+100	.5
+200	3.0
+230	4.0
+325	12.0
-325	80.5
TOTAL	100

Oxygen Content of Pure Aluminum Powder
0.50 ± 0.05 Percent

Figure 2. Particle Size Analysis of the Aluminum Powder.



(a) Longitudinal Section (10X)

(b) Transverse Section (10X)

Figure 3. Sections Showing Fiber Alignment (Longitudinal) and Filament Distribution (Transverse) in an As-Pressed Bar Specimen.

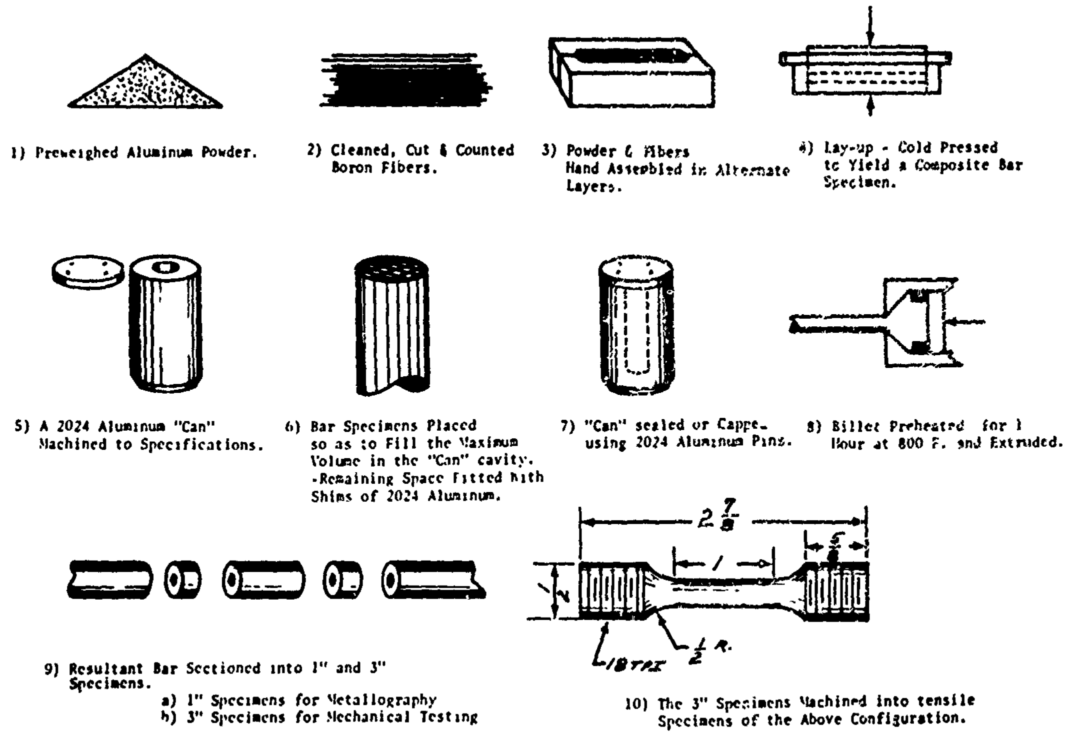


Figure 4. Schematic Diagram of Extrusion Process.

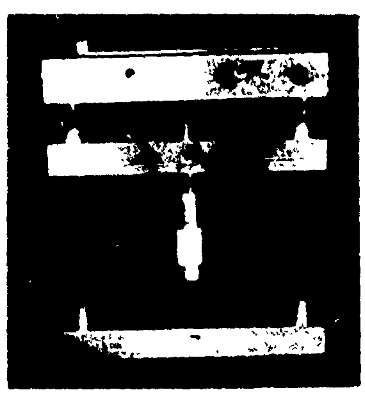


Figure 5. Jig Utilized to Aid in Controlling Vertical Spacing of Fibers in Lay-Up Procedure.

(a) Longitudinal Section (4X) (b) Transverse Section (4X)

Figure 6. Typical Example of Filament Alignment (a) and Filament Distribution (b) as a Result of the Hot Extrusion Process.

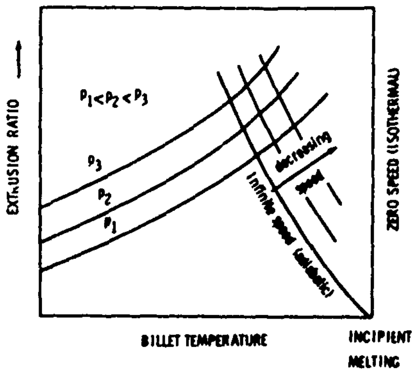


Figure 7. Schematic Diagram Showing Interdependence of Temperature, Pressure, and Extrusion Speed.

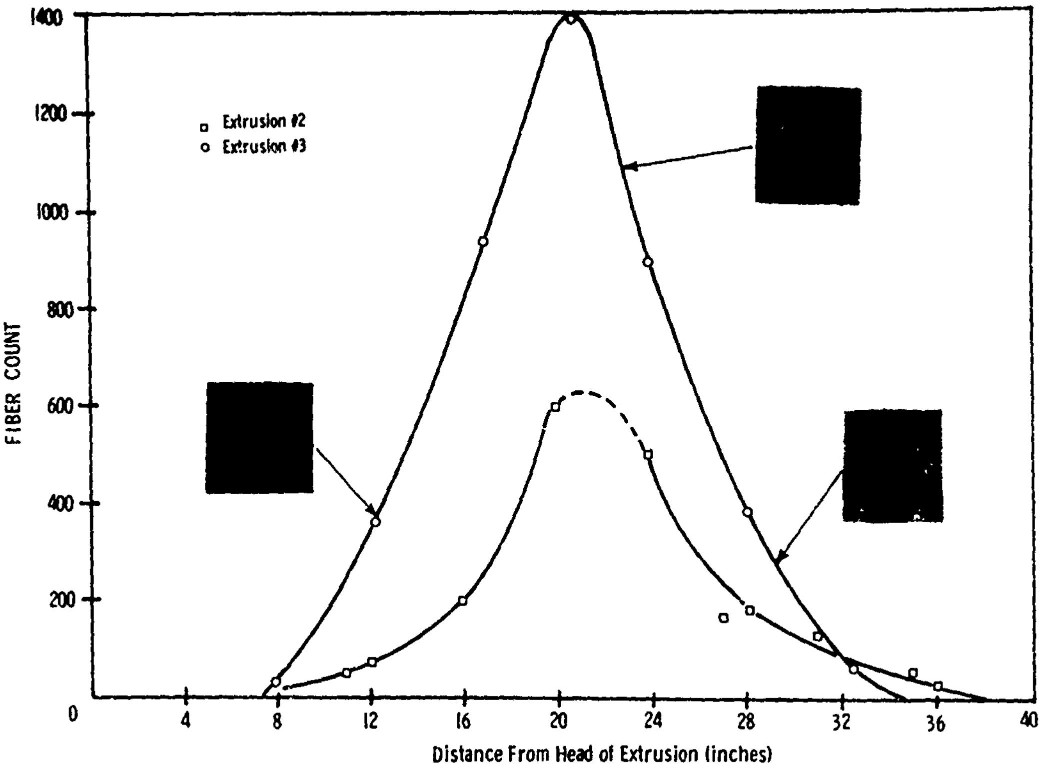


Figure 8. Relationship Between the Number of Filaments Per Cross Section (Actual Count) and the Distance from the Head of the Extruded Bar. Representative Leached Filaments (1/2 size) and Their Respective Locations.

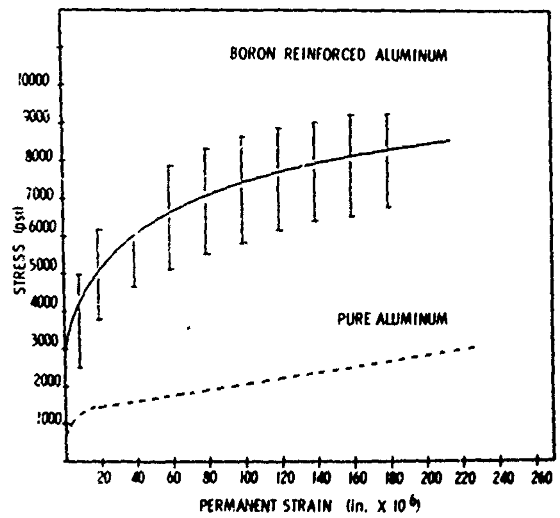


Figure 9. The Amount of Permanent Strain for a Given Stress (Comparison of Composite and Pure Aluminum).

(a)

(b)

Figure 10. (a) Etched Fracture Area Showing Deformation or Yielding of the 2024 Alloy Present in the Gage Section of Certain Tensile Specimens (4X). (b) Etched Fracture Area Showing Failure of Alloy (can material) Prior to Complete Specimen Failure (4X).

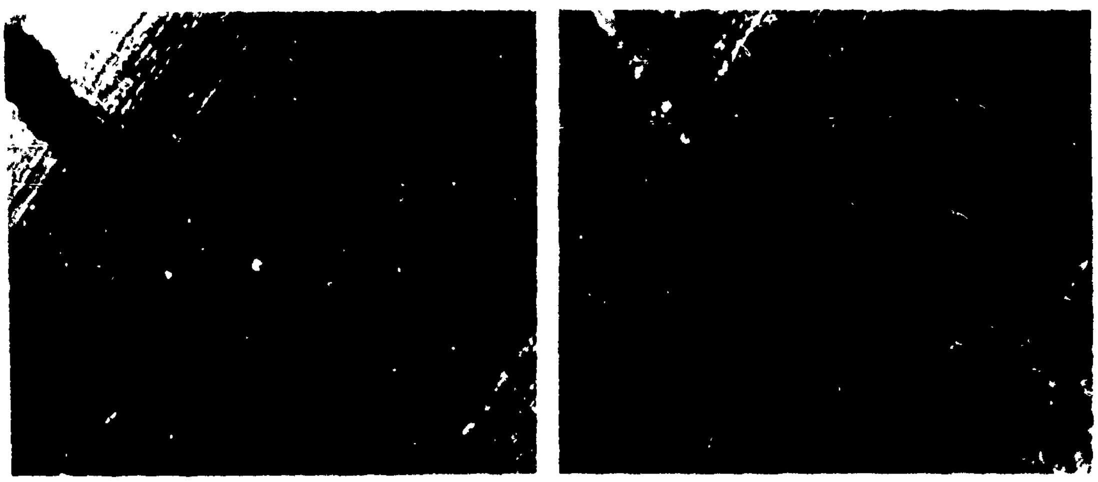


Figure 11. Effect of Fiber Presence on Crack Propagation (35X) (Reduced for Printing).

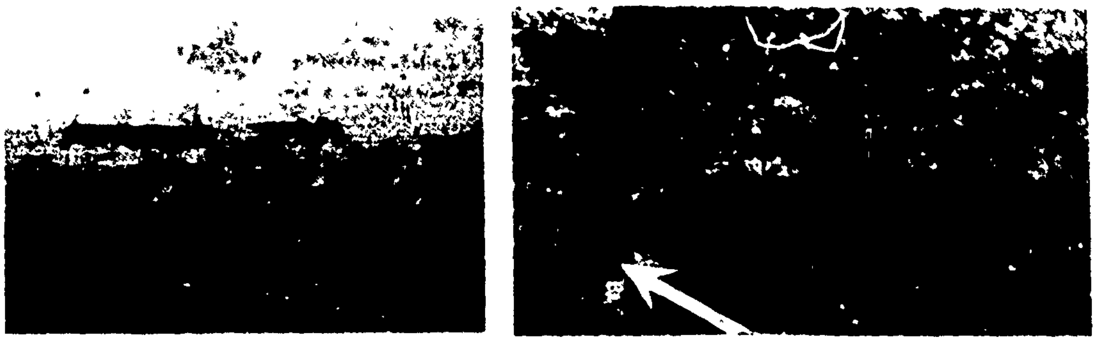


Figure 12. Fibers on Surface of Tensile Specimen. (Note Restraining Effect the Fiber Has on Surrounding Matrix-- This Tends to Indicate Adequate Bonding).

Note That When Fiber Fractures to Lengths Which Are Less Than That Necessary to Transfer a Stress, the Void so Created Can Serve as a Crack Propagation Site.

(a)

(b)

(c)

(d)

Figure 13-a,b. Fracture Surfaces of Selected Tensile Specimens (#8, 10 - Third Extrusion). Matrix Areas Which Were Void of Filaments and Hence Did Not Experience a Type of Tri-Azial Restraint, Went into Gross Yielding (Arrow).

Figure 13-c,d. Replicas of Fracture Surface Which Was Void of Filament Showing Evidence of Ductility.

(a) Degree of Fiber Bonding (140X)

(b) Mode of Fracture (400X)

Figure 14. Appearance of Filaments Extending from Fracture Surface.

Figure 15. Surface of Tensile Specimen Showing Restraint Effect of Boron Filaments on the Matrix. (Note that Areas Void of Filaments Show MacroSlip and Yielding.)

PROPERTIES OF ALUMINUM/BORON COMPOSITES FABRICATED BY HOT EXTRUSION

Specimen Number	Volume Percent Filament	Modulus Elasticity, psi	Yield* Strength, psi	Tensile Strength**, psi Apparent	Corrected	Total Elongation
2- 16	1.6%	10.7×10^6	-	20.9×10^3	17.4×10^3	9%
14	3.7	11.8	-	18.0	17.7	6.8%
12	4.16	12.0	16.5×10^3	19.8	19.5	4.9%
8	4.74	12.2	16.5	19 9	19.9	4.6%
10	5.95	13.2	16.5	19.7	19.7	3.9%
3- 4	2.8	11.1	13.0×10^3	16.7	-	9.6%
14	5.7	10.7	12.0	17.2	-	12.1%
6	9.6	14.2	16.6	18.8	-	3.1%
12	9.7	13.3	12.0	17.8	-	3.0%
10	12.1	17.2	16.5	17.0	-	2.2%
8	12.4	16.6	15.4	17.7	-	2.5%

*Based on 0.2% offset.

**Some of the specimens contained 2024 can material in gage section after machining. These strips of 2024 alloy at the specimen surface were observed to fracture before the composite portion of the specimen, and the failure of the 2024 material was accompanied by a load drop on the load-elongation curve, followed by further elongation of the composite portion. "Apparent" tensile strength values refer to load recorded immediately after fracture of 2024 material and the cross-sectional area of only the composite portion of the specimen.

Figure 16. Properties of Aluminum/Boron Composites Fabricated by Hot Extrusion.

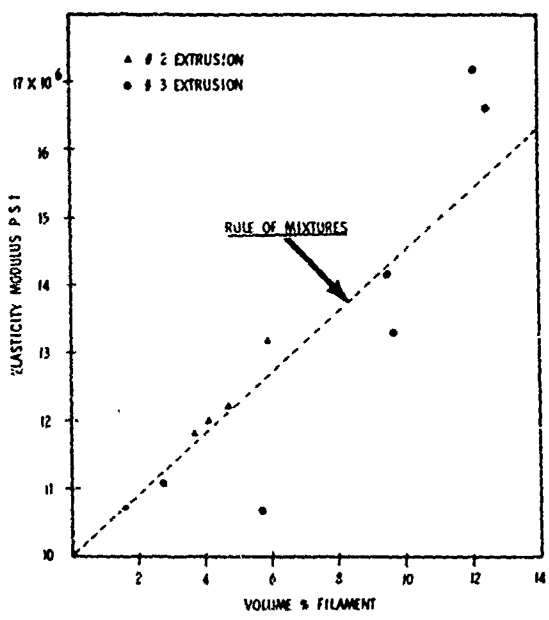
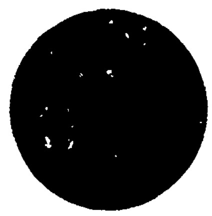
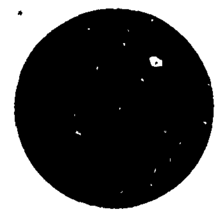


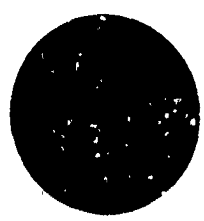
Figure 17. Chart Showing Comparison of Theoretical Rule of Mixtures (Dotted Line) with Actual Test Data.



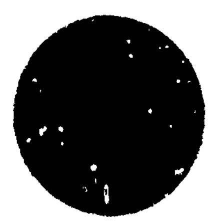
Specimen #4



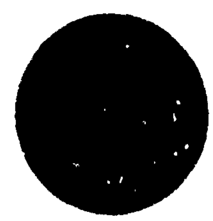
Specimen #6



Specimen #8



Specimen #10



Specimen #12

Figure 18. Cross Sections of Tensile Specimens Showing Fiber Distribution Near Fracture Zone. (Third Extrusion)

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13. ABSTRACT

This study was performed to ascertain the feasibility of forming a boron fiber-reinforced aluminum composite by a hot extrusion process. Post-extrusion examination revealed that fiber breakup was excessive, but the length to diameter ratio for most of the filaments was great enough to effect a stress-transfer. Thus, both modulus and strength values increased as the volume percent fiber in the specimens increased.

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